The Realm of the Low-Surface-Brightness Universe
Proceedings IAU Symposium No. 355, 2019
D. Valls-Gabaud, I. Trujillo & S. Okamoto, eds.

© 2019 International Astronomical Union
DOI: 00.0000/X000000000000000X

Measuring energy production in the Universe over all wavelengths and all time

Simon P. Driver

International Centre for Radio Astronomy Research (ICRAR), University of Western Australia, 35 Stirling Highway, Crawley, Perth, WA6009, Australia

arXiv:2102.12089v1 [astro-ph.CO] 24 Feb 2021

Abstract. The study of the extragalactic background light (EBL) is undergoing a renaissance. New results from very high energy experiments and deep space missions have broken the deadlock between the contradictory measurements in the optical and near-IR arising from direct versus discrete source estimates. We are also seeing advances in our ability to model the EBL from γ-ray to radio wavelengths with improved dust models and AGN handling. With the advent of deep and wide spectroscopic and photometric redshift surveys, we can now subdivide the EBL into redshift intervals. This allows for the recovery of the Cosmic Spectral Energy Distribution (CSED), or emissivity of a representative portion of the Universe, at any time. With new facilities coming online, and more unified studies underway from γ-ray to radio wavelengths, it will soon be possible to measure the EBL to within 1 per cent accuracy. At this level correct modelling of reionisation, awareness of missing populations or light, radiation from the intra-cluster and halo gas, and any signal from decaying dark-matter all become important. In due course, the goal is to measure and explain the origin of all photons incident on the Earth's surface from the extragalactic domain, and within which is encoded the entire history of energy production in our Universe.

Keywords. cosmology: diffuse radiation, cosmology: observations, galaxy: evolution

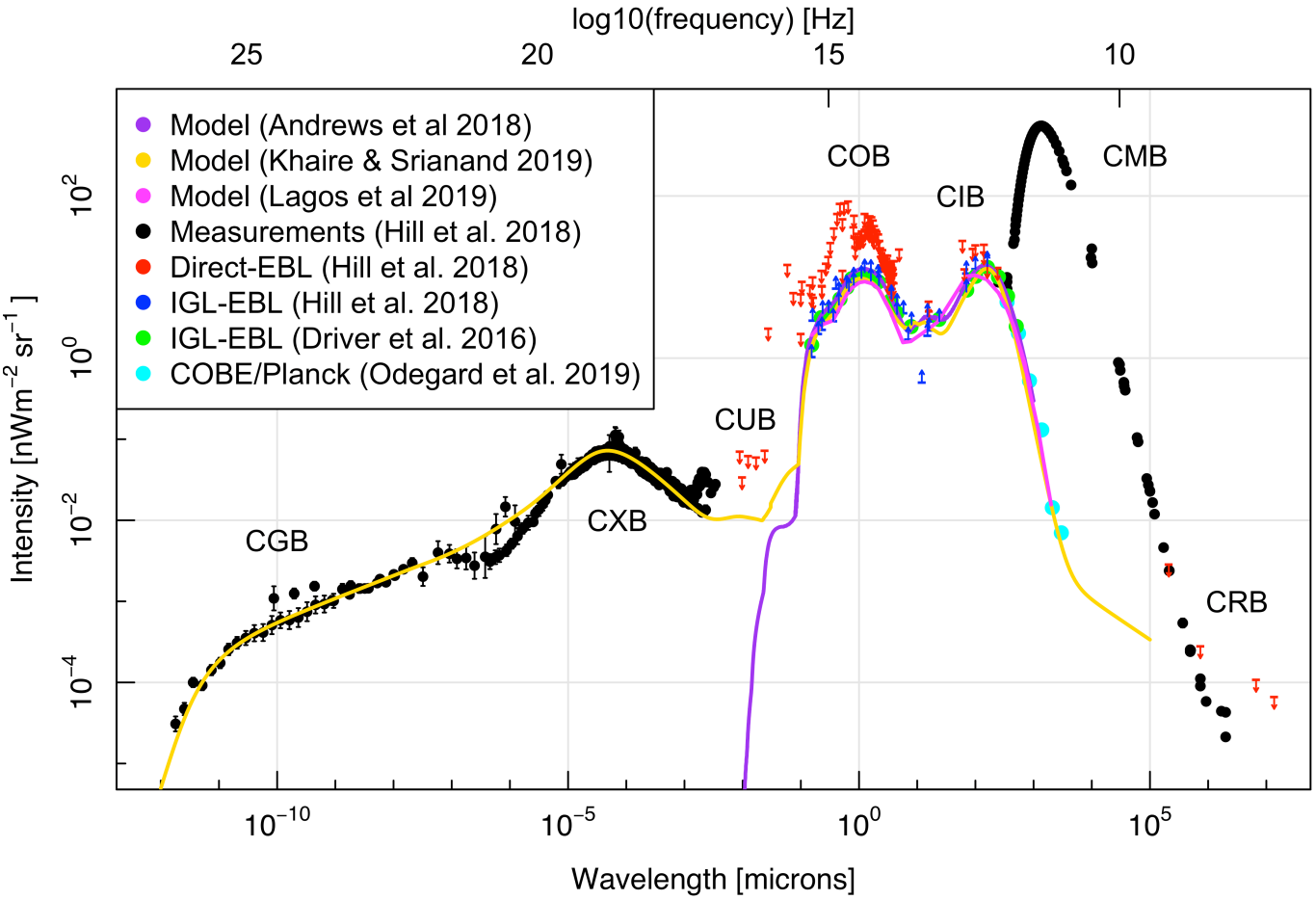

Figure 1. A compendium of recent EBL measurements, mainly based on data assembled by Hill, Masui & Scott (2018) and also including the Andrews *et al.* (2018) UV-far-IR model (purple line), the recent semi-analytic Shark model (Lagos *et al.* 2019, , in magenta) and the Khaire & Srianand (2019) γ-ray to radio model (gold line).

1. Introduction

The extra-galactic background light (EBL, see review by Mattila & Väisänen 2019), represents the radiation incident from a steradian of extragalactic sky onto a square metre of the Earth's atmosphere, i.e., the photon-flux that originates from outside our Galaxy. Encoded in the EBL is the entirety of photon production pathways that have existed from the Big Bang to the present day. This is a remarkable concept, as to measure and model the EBL, is to explain all photon-energy production over all time.

Fig. 1 shows a recent compendium of EBL measurements, primarily taken from Hill, Masui & Scott (2018), but augmented with some additional data from COBE/Planck (Odegard *et al.* 2019), the recent UV to far-IR model from Andrews *et al.* (2018) (purple line), a recent semi-analytic model from Shark (Lagos *et al.* 2019), and the more extended panchromatic model from Khaire & Srianand (2019) (solid gold line). This overall EBL can be subdivided into a number of "backgrounds", as indicated, each spanning specific wavelength ranges, with the distinction driven mostly by the technologies required to obtain the measurements.

The most notable contributor is the Cosmic Microwave Background (CMB), arguably not actually part of the EBL, which dominates the incident flux in terms of photon number and photon energy. The CMB sits slightly apart from the other backgrounds, in that it originates from the energy remains of the early Big Bang era leading up to decoupling. The remainder of the EBL is made from photon-production mechanisms which have occurred *since* decoupling.

At about 10 per cent of the CMB, are the Cosmic Optical Background (COB) and the Cosmic Infrared Background (CIB). There are three key processes at play here (see for example Gilmore *et al.* 2012; Andrews *et al.* 2018; Khaire & Srianand 2019): star-formation; accretion of material onto black holes (predominantly AGN activity); and dust reprocessing in which approximately half of the photons generated in the former two phases are attenuated by dust grains within the host system and reradiated in the far-IR (Dunne *et al.* 2003; Driver *et al.* 2008).

The Cosmic Ultraviolet Background (CUB) and Cosmic Radio Background (CRB) are less well studied (see Hill, Masui & Scott 2018, for a summary of both backgrounds), and represent fertile ground for future investigation and modelling (see in particular discussion of the CUB in Khaire & Srianand 2019). Currently these are primarily constrained by observations from the Extreme Ultraviolet Explorer (EUV), and a relatively small number of radio surveys.

Finally, we have the high-energy Cosmic γ-ray background (CGB; see for example Ajello *et al.* 2015) and the Cosmic X-ray Background (CXB; see for example Cappelluti *et al.* 2017). These are fairly well constrained and comprised of photons originating from high-energy processes such as x-ray binaries, AGN, cooling of gas, supernovae, and shock events: essentially plasma astrophysics. And a rich area for placing constraints on decaying dark matter models, for example Brdar *et al.* (2018).

Because of the energy dominance of the COB and CIB these are, after the CMB, the most studied wavelength regions and the main focus of this article. However, before moving on, it is worth advocating the need for further work in particular soft x-ray, extreme ultraviolet, radio, and very high ($> TeV$) scales. All of these windows, except for the EUV (see Cooray *et al.* 2016), are being extended through new facilities, e.g., the upcoming Cherenkov Telescope Array, the recently launched eROSITA satellite, and higher sensitivity wide and deep radio surveys at short (ASKAP, MeerKAT), and long wavelengths (LOFAR, MWA). The extreme-UV however looks destined to remain fairly uncharted territory, with no obvious plans for a space mission to cover this wavelength region (although we note the proposed *Messier* mission — see these proceedings — will extend down to 0.15micron). One motivation to push further into the EUV might be the recent study of Mattila *et al.* (2017a) who used dark cloud observations to detect an anomalous UV photon-flux increasing into the UV (Mattila *et al.* 2017b): could this be an interesting future window for decaying dark-matter searches?

2. The optical controversy

Most obvious from Fig. 1 is a significant disparity in the COB and to some extent the CIB. Fig. 2 shows a zoom in of this region which now includes the errorbars associated with the measurements. These estimates predominantly fall into two camps: Observations from direct background measurements (direct-EBL); and observations from integrated galaxy counts (IGL-EBL). The former method should capture *all* the photon flux, whereas the latter only captures the photon-flux from discrete detectable sources, i.e., galaxies and quasars. The fact that the direct-EBL measurements can be a factor of 4—10$\times$ above the IGL-EBL, can have a number of possible explanations. The least exciting is that one method is simply in error. The most exciting is that there are significant unknown photon-production pathways occurring outside of the detectable galaxy population. Possibilities for the latter might include missing populations of diffuse galaxies, excessive stripped gas, photon-production from a diffuse component of the IGM via some unknown process, or more exotic possibilities such as decaying dark-matter or dark-mater/matter interactions. Regardless, it is clearly important to understand the nature of this discrepancy.

Direct-EBL estimates are typically taken from measurements of the absolute sky background from well calibrated detectors, most notably data from the *Hubble Space Telescope*, which sits above the Earth's atmosphere. However, this still requires further background subtraction of the Zodiacal Light (Zodi) and any Diffuse Galactic Light (DGL).

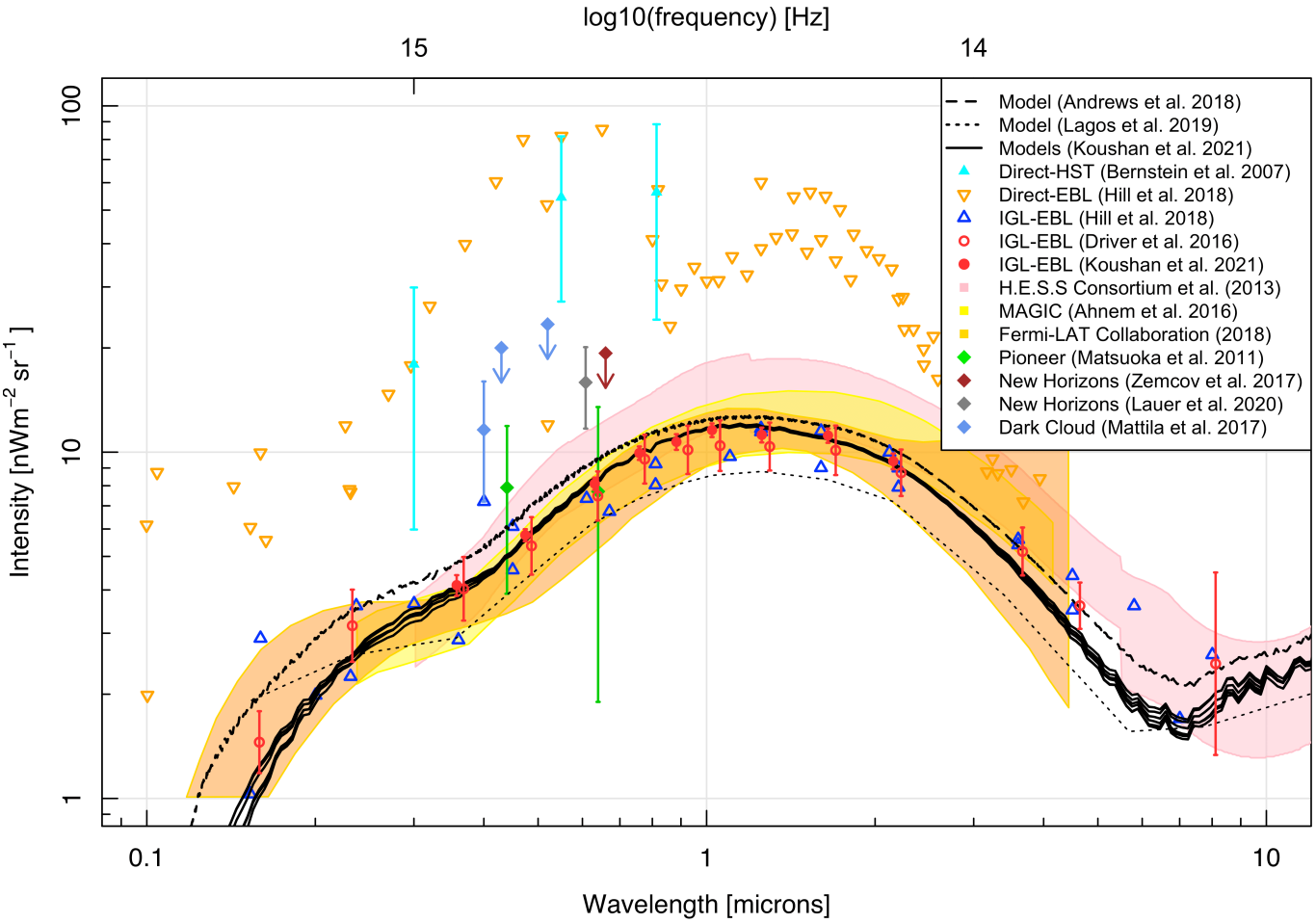

Figure 2. A zoom in of the COB and CIB region from Fig. 1, but including data from the Very High Energy experiments and deep space probes Pioneer 10/11 and New Horizons. These seem to corroborate the IGL-EBL measurements.

Fig. 3 highlights this issue by showing the flux of various components including that from the Earth's night sky, the Zodi (dependent on Ecliptic coordinates), the Diffuse Galactic Light (dependent on Galactic coordinates), the EBL (isotropic), and the component of the EBL from reionisation (isotropic but with a highly uncertain shape and amplitude). Very roughly the Zodi is about 10 per cent of a dark site moon-less night sky, the EBL 1-10 per cent of the Zodi, the EBL and DGL comparable (with the latter highly dependent on direction), and the reionisation signal 1 per cent of the EBL (see Zemcov *et al.* 2011; Cooray *et al.* 2012, for more details). Hence the near-IR reionisation signal is around a thousandth of a per cent of the Earth's night sky flux. Moreover, a 1 per cent systematic error in the subtraction of the Zodi can lead to a 100 per cent error in direct measurements of the EBL (a point well made by Berstein 2007). HST, of course sits mostly above the atmosphere but at the start and end of an observation the telescope's attitude can encroach on the Earth's limb introducing a component of Earth-shine (i.e., some additional small fraction of the night-sky spectrum).

The IGL-EBL estimates come from combining galaxy number-counts from the widest and deepest imaging across multiple wavebands. This also requires some extrapolation at very faint and very bright magnitudes (see for example Driver *et al.* 2016). Recently, with advances in very wide (e.g., GALEX, SDSS, VST KiDS, WISE etc), and very deep surveys (e.g., HST Candles etc), most optical and near-IR bands have number-count gradients which can be seen to gradually flatten from the canonical bright non-expanding Euclidean expectation of $\delta \log_{10} N(m)/\delta m = 0.6$ to below 0.4, the gradient of maximum contribution to the overall luminosity density. Assuming the counts continue to decline in a monotonic fashion the IGL-EBL is therefore bounded and measurable with a relatively small extrapolation error. Fig. 4 highlights how an IGL-EBL constraint is made for a particular waveband. The left-panel shows the raw galaxy number-counts from a number of surveys, and the right-panel shows the contribution of each magnitude interval to the overall IGL-EBL measurement. The IGL-EBL is recovered by integrating under the right-panel curve with a model-fit, or an extrapolated spline-fit (see for example Driver *et al.* 2016). The concern with the IGL-EBL method, is whether surveys are missing populations of very diffuse galaxies leading to an underestimation of the number-counts. The relatively good agreement between number-count data from so many heterogeneous depth datasets would suggest this is not the case, but nevertheless the issue does remain a valid concern at some level.

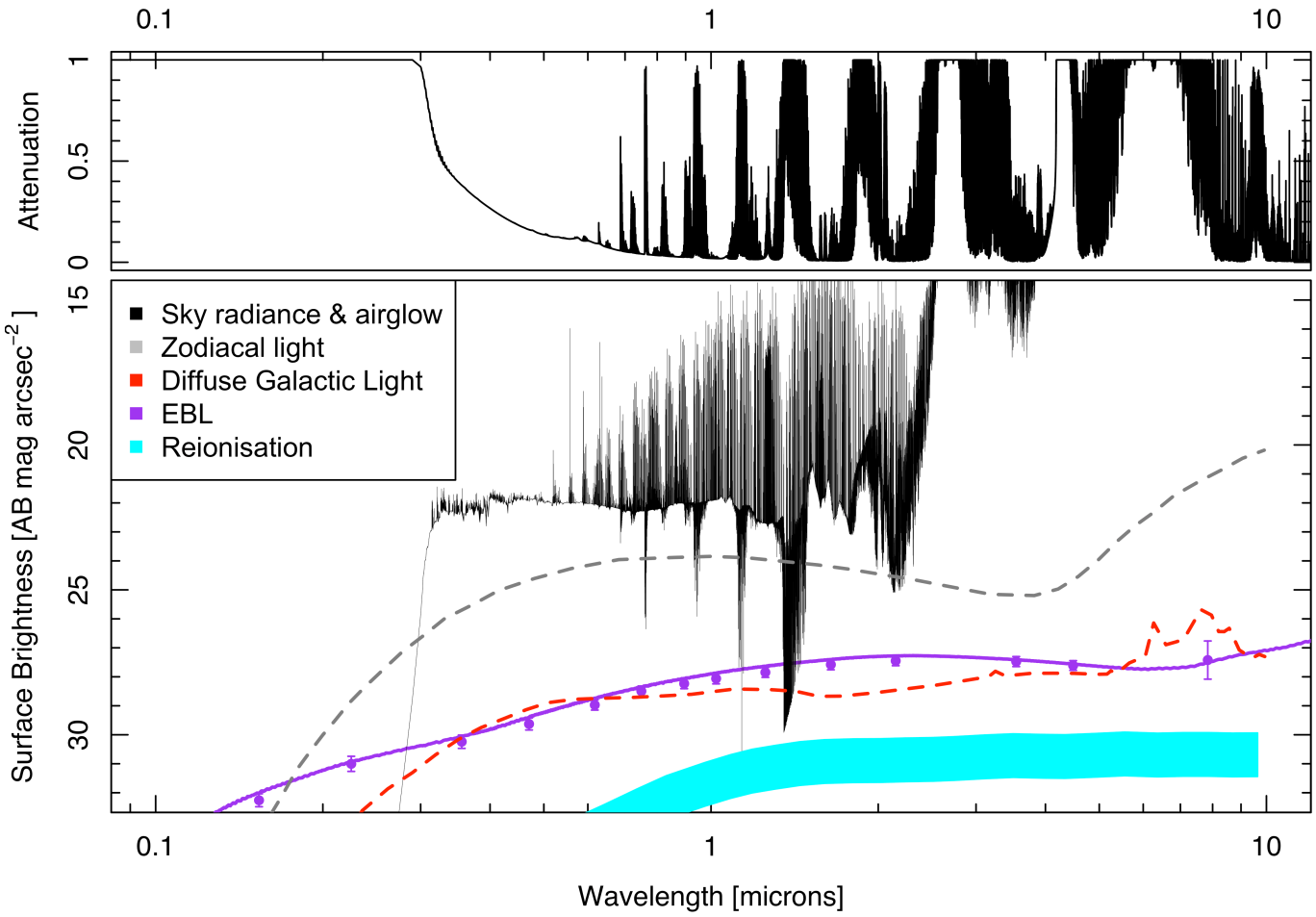

Figure 3. (*main panel*) The spectral energy distributions of various backgrounds including, the night sky, zodiacal light, the extragalactic background light, the diffuse Galactic light, and the expected signal of reionisation. The figure is shown in atypical units of Surface Brightness in AB mag/arcsec^2. (*top panel*) The attenuation of external radiation by the Earth's atmosphere.

3. Very High Energy and deep space missions to the rescue

Recently, the disparity in Fig. 2 appears to at least be partially resolved from the inclusion of two new lines of argument: Very High Energy (VHE) constraints, and measurements from the Pioneer 10 & 11 (Matsuoka *et al.* 2011) and New Horizons (Zemcov *et al.* 2017; Lauer *et al.* 2021) deep space probes which are sufficiently far from the Sun for a much diminished Zodi background (Bock 2012; Cooray *et al.* 2016).

VHE studies rely on the interaction of the expected power-law distribution of GeV photons from distant Blazars preferentially interacting with $\sim$ 1micron photons within the EBL through the production of e^+e^--pairs. This integrated interaction along the pathlength of the TeV radiation results in a decrement in the received Blazar spectrum at energies where the interaction is expected to be maximum. This method requires the adoption of a COB model, and the VHE data constrains the amplitude of the model. Recently the H.E.S.S. and MAGIC teams reported the need for a small upward normalisation over the IGL-EBL data of just 20 per cent, with about a 20 per cent uncertainty, i.e., essentially consistent. More recently the largest study to date from the Fermi-LAT collaboration of $\sim$ 750 Blazars reported full consistency with the IGL data (Fermi-LAT Collaboration 2018). The VHE results are shown as the three solid bands on Fig. 2. Current efforts are also underway to constrain not only the normalisation, but the actual COB spectral energy distribution shape. This is significantly harder but starting to place useful constraints on the COB SED, see for example Biteau & Williams (2015) and VERITAS Collaboration (2019).

The Pioneer 10/11 and New Horizons deep space probes, both contain relatively stable imaging cameras and these cameras which can be used for direct-EBL measurements (see Matsuoka *et al.* 2011; Zemcov *et al.* 2017; Lauer *et al.* 2021). As Zodiacal light strongly drops as one moves out in the Solar System (see Bock 2012; Cooray *et al.* 2016), its overwhelming impact is diminished and its accurate subtraction less problematic. Unfortunately the field-of-view of the onboard cameras are small and sensitivity poor. One cannot also not entirely rule out some degradation of the system throughput and response functions with time. Nevertheless the three studies to data show a consistent picture and agree more closely with the IGL-EBL data, albeit with fairly large errorbars (see Fig. 2. Note that Koushan *et al.* (2021) have now decreased the uncertainty on the EBL-IGL measurements to $<$ 5 per cent.

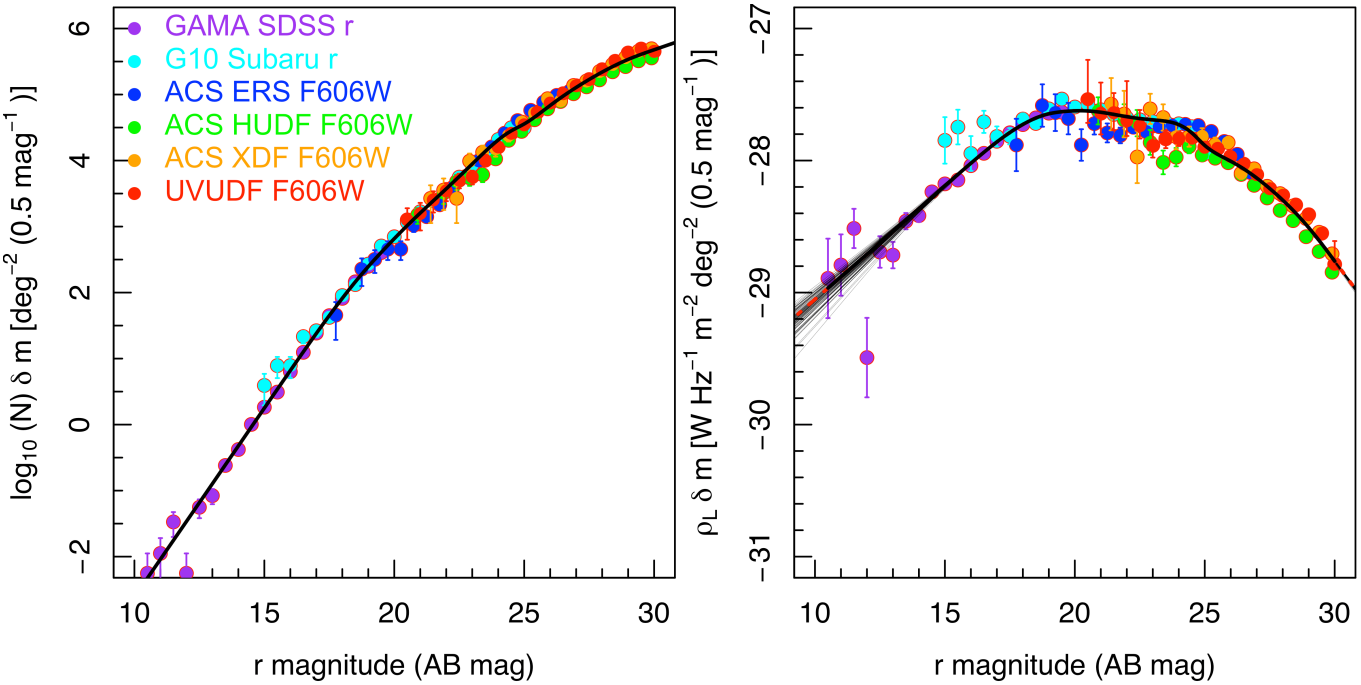

Figure 4. The IGL method relies on assembling galaxy number-counts (*left panel*) and then integrating the flux contribution of each magnitude interval (*right panel*). Note that in most optical/near-IR bands the contribution is well bounded with minimal extrapolation required, and that the peak contribution is at relatively intermediate magnitudes. Improvements will come not from deeper or wide data but improved methodologies in flux measurements and sample sizes at the mid-mag range.

4. Entering the era of precision EBL studies

The recent VHE and deep space data appear to provide compelling evidence that the IGL-EBL measurements pretty much represents the full COB to within ∼20 per cent (Driver *et al.* 2016), with little room for significant photon-flux from new populations, diffuse light, decaying dark matter or any other furphy, at least arising in optical wavebands. To first order this looks to confirm that our understanding of the amount of star-formation that has occurred in the Universe over all time is correct to within around 20 per cent, i.e., the current level of error and scatter in the IGL, VHE, and deep space constraints. A 20 per cent uncertainty, however, is still significant and could easily mask a *modest* population of diffuse low surface brightness galaxies, or other photon-production pathways. This then motivates the reduction of the errors through direct-EBL, VHE and IGL-EBL methods to somewhere around the 1 per cent level. A goal which would represent a remarkable empirical feet but also entirely attainable with the next decade.

5. The SkySURF program

While the discrepancy in the HST direct-EBL estimates and the IGL-EBL data appears to be resolved, the explanation for the discrepancy is still not known but cannot be extragalactic. There are a number of obvious possibilities. The first is a limited understanding of the Zodiacal Light in the inner Solar System, which in turn implies a limit in our understanding of the Solar System dust distribution and properties. The second is an additional source of contamination in HST data, plausibly a component of Earth-shine given HST's relatively low-orbit and the tendency to pack orbits close to the Earth-limb. A more radical and exciting prospect might be additional optical radiation emanating from the Galactic Halo, or a brighter than expected contribution from the DGL.

Led by Prof Rogier Windhorst and Dr Rolf Jansen at Arizona State University, a team of US and Australian scientists are looking to address this by reprocessing the entire HST Advanced Camera for Surveys and Wide-field Camera 3 archive, as part of an HST Cycle 27—29 SkySURF Archival program (AR-15810). The goals are to conduct both direct-EBL sky measurements, as well as obtain refined medium/deep galaxy number-counts using our new source finding code ProFound (Robotham A. *et al.* 2018), to also improve the IGL-EBL constraints.

The direct measurements, in particular, will be used to untangle the three distinct backgrounds: the Zodi, the DGL, and the EBL; by using their distinct positional dependencies: Ecliptic, Galactic, and isotropic respectively.

The HST number-count measurements will be combined with similar work underway for the European Southern Observatory's Visible Survey Telescope (VST) and Visible Infrared Survey Telescope (VISTA) kilo-degree surveys (KiDS and VIKING respectively). Combined VST, VISTA and HST data will therefore provide a homogeneously defined set of galaxy number-counts from u to K and from AB 10th to 30th magnitude. However, significant systematics need to be overcome related to issues such as star-galaxy separation, galaxy fragmentation, over-blending, and the aforementioned sensitivity to diffuse populations.

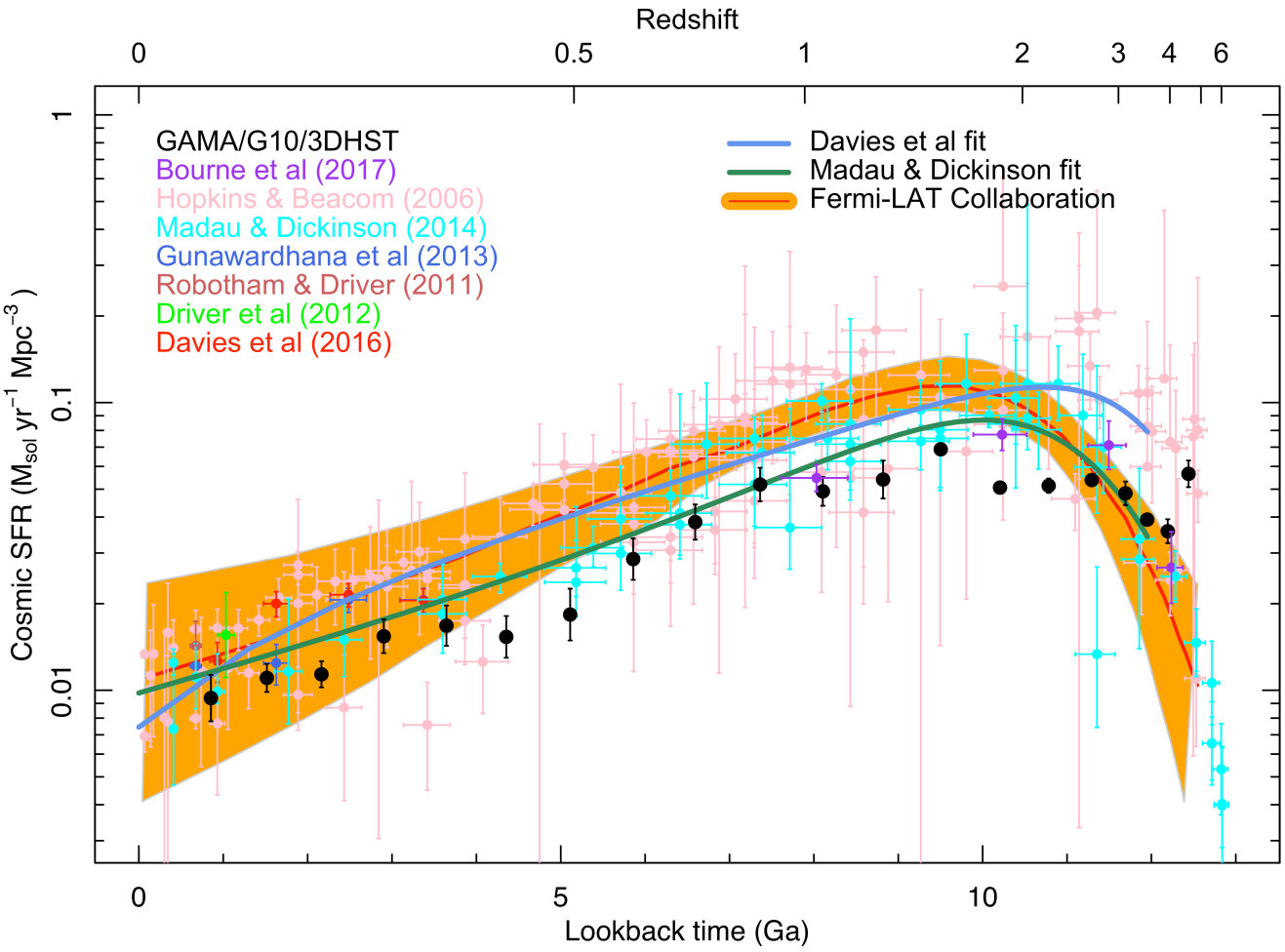

Figure 5. The latest cosmic star-formation history plot used as the starting point for our model and including the recent VHE constraints from the Fermi-LAT Collaboration (2018).

6. The state of EBL modelling: phenomenological and *apriori*

In addition to SkySURF, there are a number of upcoming wide and deep missions which will contribute significant new data in the coming years. In particular high-resolution imaging data from new space-platforms: Euclid, JWST, and Roman, and extremely wide ground-based data from LSST. These should provide the statistical power to reach that 1 per cent goal for the COB within a decade.

At the 1 per cent level interesting astrophysics arises and in particular the direct contribution of reionisation becomes quantifiable, as does the contribution from Intra Cluster Light (ICL), Intra Group Light (IGL), Intra Halo Light (IHL), tidal streams, and a myriad of other physical processes.

At the present time there are a number of approaches to modelling the EBL, which can be grouped under *apriori* models and phenomenological models. Examples of the *apriori* approach arise from numerical, semi-analytic and hydro-dynamical simulations such as Gilmore *et al.* (2012), Inoue *et al.* (2013), Cowley *et al.* (2019), Lagos *et al.* (2019), and Baes *et al.* (2019). Examples of the phenomenological model include our own work Andrews *et al.* (2018); Koushan *et al.* (2021), along with those of Domínguez *et al.* (2011) and Khaire & Srianand (2019).

Here in brief we summarise our own model, described in full in Andrews *et al.* (2018), which starts with two simple axioms: (1) the formation of today's spheroid and bulge stars dominated the cosmic star-formation history at high redshift, and (2) AGN growth and activity is closely linked to spheroid and bulge star-formation. The basis for the former is that the oldest known stars are found in the Galactic Centre (Zoccali *et al.* 2006), and for the latter we cite the Gebhardt-Magorrian relation (Gebhardt *et al.* 2000; Magorrian *et al.* 1998).

In addition we require a few further decisions around the cosmic star-formation history (see Fig. 5), an adopted stellar population synthesis code, a dust attenuation model, and a metallicity history. Here we adopt an invariant Chabrier IMF, the galaxy and AGN dust attenuation models of Dale *et al.* (2019), and a metallicity evolution which linearly tracks the star-formation history. With these two axioms and the choices above, we can produce the purple line shown in Fig. 1. This maps the currently measured COB/CIB portion of the EBL to within 30 per cent accuracy, i.e.,

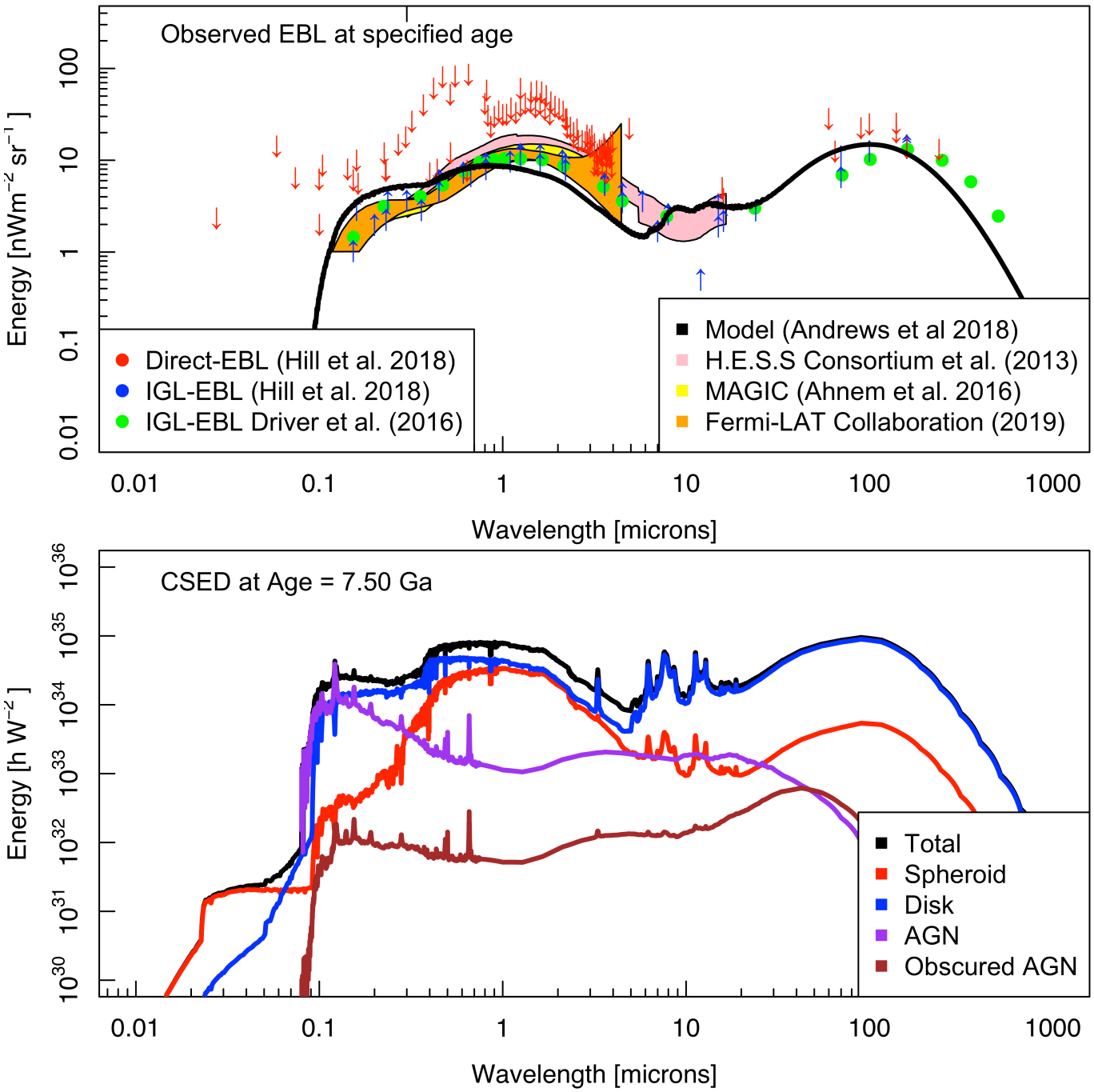

Figure 6. A static frame from our EBL/CSED movie, which shows the build up of the EBL over time. (*upper panel*) the EBL data as observed today with the EBL as it would be if observed when the Universe was 7.5Ga. (*lower panel*) the instantaneous cosmic spectral energy distribution (CSED) at an age of 7.5Ga, showing the contribution to the EBL from various components at this time-step (as indicated). The endpoint of the movie is the purple curve shown on Fig.1

comparable to the measurement error, across the entire optical to far-IR wavelength range, with only some tweaking of the AGN component required to match the UV data.

Essentially this provides a self-consistency test by which the adopted Cosmic Star-formation History (see Fog. 5), under the most simplistic assumptions, fully predicts the present day EBL. Moreover the model not only predicts the EBL, but energy (photon) production at any time over the past 13 billion years. This is highlighted by the snapshot from our linked movie (Fig. 6), which shows the EBL (upper) and Cosmic Spectral Energy Distribution (CSED; lower) at a time when the Universe was 7.5Ga. In the upper panel we show the redshift zero EBL measurements, i.e., the endpoint to where the EBL will eventually grow to match, and the EBL as it would be observed at an age of 7.5Ga, i.e., in its fairly fledgling state. In the lower panel we show the instantaneous energy being produced by the four components (as indicated). The CSED, sub-divided into spheroid, disc obscured and unobscured AGN contributions, is potentially far more powerful than the EBL, as it dissects the EBL across time and providing a clear falsifiable prediction as our measurements improve. In due course comparisons between CSED measurements (Andrews *et al.*

2017) and models (Andrews *et al.* 2018; Baes *et al.* 2019; Lagos *et al.* 2019) have the potential to constrain many of the assumptions adopted in the model (see, in particular, Koushan *et al.* 2021).

7. Prognosis and future directions

The prognosis for the EBL and its subdivision into time slices are remarkably good, with significant effort underway on a number of fronts which will rapidly advance both the empirical measurements and our capacity to model the data. Critical will be the complement of upcoming deep and complete spectroscopic campaigns to allow for the deconstruction of the EBL into the CSED.

With the analysis of the VST KiDS, VISTA VIKING and HST SkySURF data as they stand, we should be able to attain a ~ 3 per cent measurement of the EBL from UV to near-IR wavelengths. In combination with spectroscopic and photometric redshifts we will also be able to measure the contributions of each time-interval to the EBL in coarse billion year slices extending out to half the age of the Universe with major high-density spectroscopic surveys like DEVILS (Davies *et al.* 2018) and WAVES (Driver *et al.* 2019), and beyond with ESO MOONS and Subaru PFS.

Modelling this data will present both a challenge and an opportunity for to the simulation community. The HST SkySURF project will also likely lead to advances in our understanding of the two key foregrounds, the Zodiacal Light and the Diffuse Galactic Light - both of significant importance in the era of precision Astronomy. With future facilities such as Messier, Euclid, JWST, Roman and LSST the prospect of a 1 per cent constraint on the UV to mid-IR portion of the EBL becomes viable.

Very, briefly we return to the even more aspirational issue of a full EBL analysis from γ-rays to radio waves. This too is likely to be transformed over the next decade with various deep and wide radio surveys allowing us to construct comparable IGL-EBL constraints over a broad wavelength range from 20cm to 10m. eROSITA will also improve upon previous measurements of the CXB, particularly at the soft x-ray end where some discrepancies are seen (see Fig. 1).

However, perhaps the most exciting prospect, is the potential to also construct CSED measurements into the x-ray and radio domains through the stacking of x-ray and radio data at the locations of known galaxies, or groups of galaxies, to directly measure the diffuse x-ray and radio continuum contributions as a function of time.

We thank the organisers for a very enjoyable and productive meeting, and look forward to continuing these discussions over what looks to be a very busy and productive decade ahead.

References

Ajello M., *et al.* 2015, *ApJ*, 800, 27
Andrews S.J., *et al.* 2017, *MNRAS*, 470, 1342
Andrews S.J. *et al.* 2018, *MNRAS*, 474, 898
Abeysekara A.U. *et al.* 2019, *ApJ*, (accepted, arXiv:1910.00451)
Baes *et al.* 2019, *MNRAS*, 484, 4069
Berstein R. 2007 *ApJ*, 666, 663
Biteau J., Williams D.A. 2015, *ApJ*, 812, 60
Bock J *et al.* 2012, *SPIE*, 4144, Astronomical Opportunities From The Outer Solar System
Brdar V., Kopp J., Liu J. & Wang X-P. 2018, *PhyRvL*, 120, 061301
Cappelluti N. *et al.* 2017, *ApJ*, 837, 19
Cooray A. Gong Y., Smidt J., Santos M.G. 2012, *ApJ*, 756, 92
Cooray A. 2016, *RSOS*, 3, 150555
Cowley W.I., *et al.* 2019, *MNRAS*, 487, 3082
Dale D.A., *et al.* 2014, *ApJ*, 784, 83
Davies L.J.M., *et al.* 2018, *MNRAS*, 480, 768
Domínguez A. *et al.* 2011, *MNRAS*, 410, 2556
Driver S.P. *et al.* 2008, *ApJ*, 678, 10
Driver S.P. *et al.* 2016a, *ApJ*, 827, 108
Driver S.P., *et al.* 2019, *ESO Messenger*, 175, 46
Dunne L. *et al.* 2003, *Nature*, 424, 285
Fermi-LAT Collaboration 2019, *Science*, 362, 1031
Gebhardt K. *et al.* 2000, *ApJ*, 539, 13
Gilmore R.C., Somerville R.S., Primack J.R., Domínguez A. 2012, *MNRAS*, 422, 3189
Hill R., Masui K. & Scott D. 2018, *Applied Spectroscopy*, 72, 663
Inoue Y., *et al.* 2013, *ApJ*, 768, 197
Lagos C., *et al.* 2019, *MNRAS*, 489, 4196
Lauer T., *et al.* 2021, *ApJ*, 906, 77
Khaire V. & Srianand R. 2019, *MNRAS*, 484, 4174
Koushan S., *et al.* 2021, *MNRAS*, in press
Magorrian J., *et al.* 1998, 115, 2285
Mattila K. & Väisänen P. 2019, *Contemporary Physics*, 60, 23 (arXiv:1905.08825)

Mattila K. *et al.* 2017a, *MNRAS*, 470, 2133
Mattila K. *et al.* 2017b, *MNRAS*, 470, 2152
Matsuoka Y., Ienka N., Kawara K., & Oyabu S 2011 *ApJ*, 736, 119
Odegard N. *et al.* 2019, *ApJ*, 877, 40
Robotham A. *et al.* 2018, *MNRAS*, 476, 3137
Zemcov M. *et al.* 2011, *Proc of Science*, arXiv:1101.1560
Zemcov M. *et al.* 2017, *Nature Communications*, 8, 15003
Zoccali M. *et al.* 2006, *A&A*, 457, 177

Discussion

A. Domínguez: What is the contribution of AGN to the EBL ?

S. Driver: In general the AGN are sub-dominant throughout, except in the UV and mid-infrared. However, we do have some unexplained flux in the ultraviolet which we currently *fix* by boosting the AGN a little. If this high UV flux really is due to AGN, then it is AGN which has kept the IGM ionised and still doing so today.